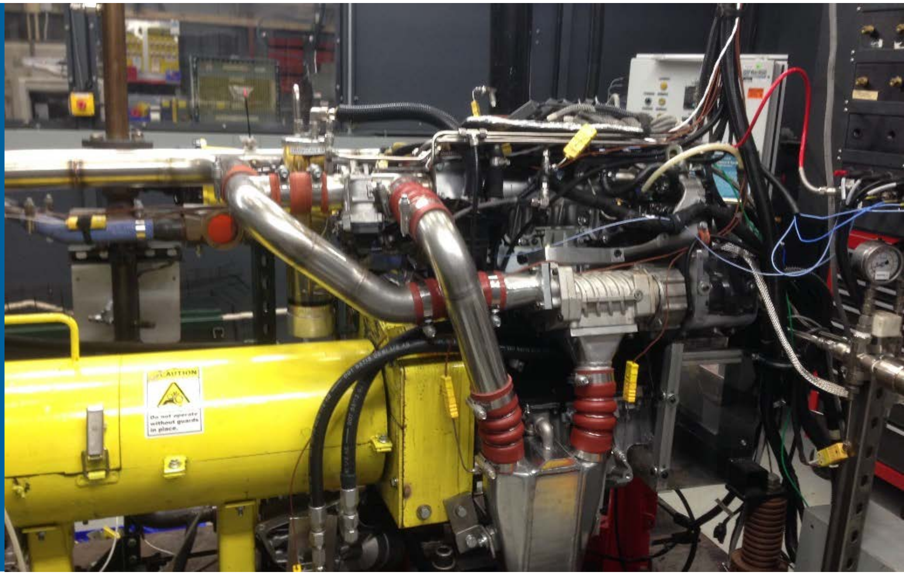
ADVANCES IN HIGH-EFFICIENCY GASOLINE COMPRESSION IGNITION



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FY17 DOE VTO Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
2:45 – 3:15 PM, Tuesday, June 6, 2017

Project ID# ACS011

OVERVIEW

Timeline

- Started Oct 2016
- End date Sept 2019
- 25% Completed

Barriers

- From MYPP
  - Mechanism to control LTC Timing
    - Addressed in FY14-15
  - LTC high load and high speed operation
    - Investigated FY17
  - LTC control during change of speed and load
    - Investigated FY17

Budget

- Total project funding
  - DOE share 100%
  - Contractor share 0%
- Funding received in
  - FY16 $470k
  - FY17 $370k
    - Reflects reduced spending rate

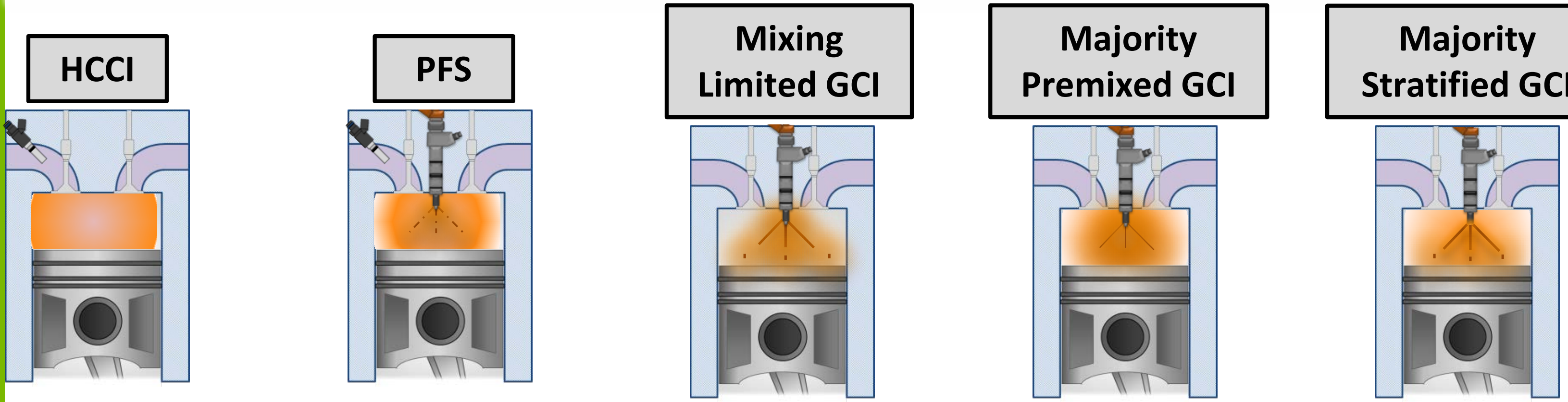
Partners

- GM R&D
  - Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
- Argonne PM experiments
  - Understand PM similarities/differences for GCI and Diesel
- Lund University
- Eaton

OBJECTIVES/RELEVANCE: MULTI-CYLINDER, HIGH EFFICIENCY GASOLINE COMPRESSION IGNITION

Long-Term Objective

Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system



Graphics courtesy ORNL (Curran & Dempsey)

Current Specific Objectives:

1. Develop injection approach for low combustion noise, FSN, and emission
2. Investigate effects of T/C boosting and LP-EGR upon gas/thermal efficiency for different loads & speeds
3. Identify a pathway to improve efficiency and meet all constraints for entire engine map
4. Investigate particle size distribution of GCI using different measurements (SMPS, EEPS, TEM imaging)

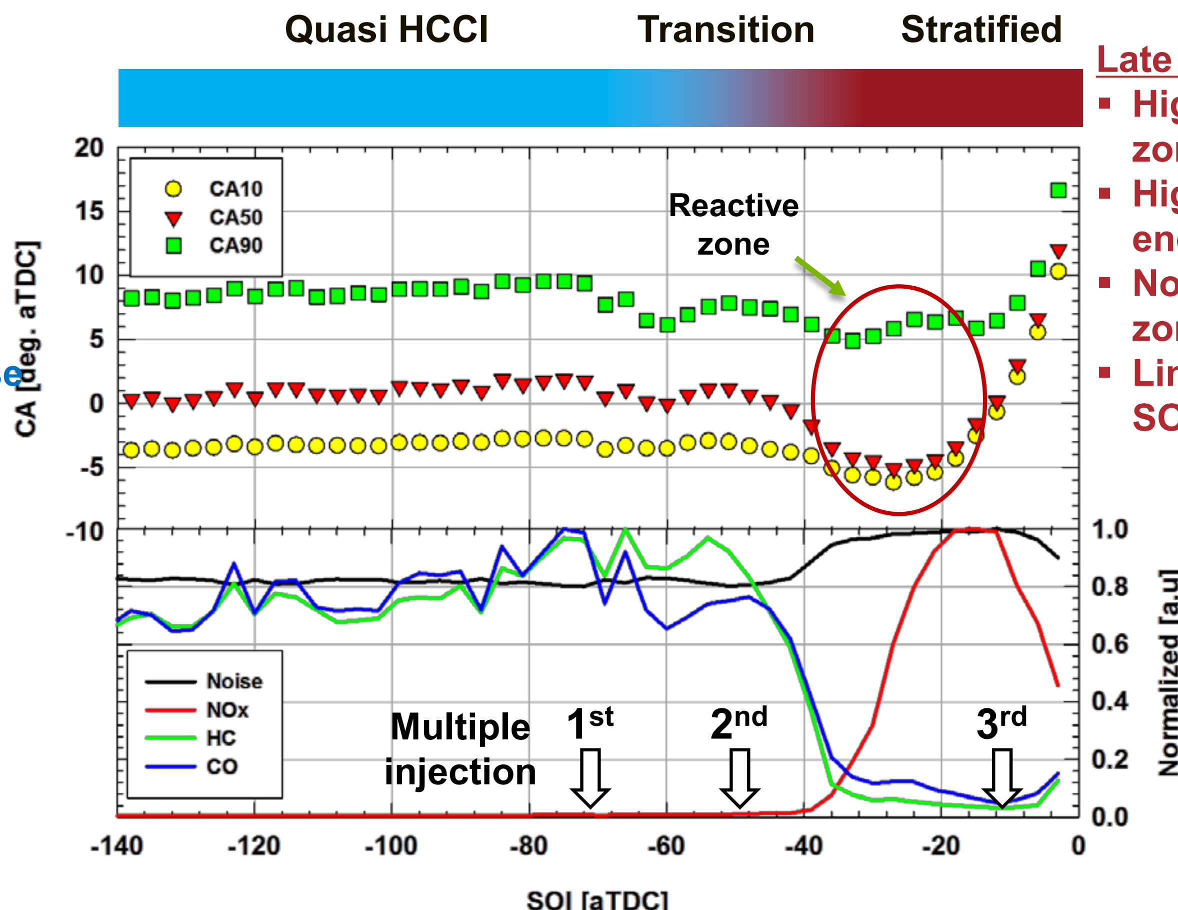
MILESTONES

Milestone	Target Date
Establish injection approach for wide range of speed/load with E10 for low combustion noise and smoke number	June 2016 (Completed)
Install new S/C pulley for increase boost operating range; an air heater was also set up at intake (ambient) air (Not covered in this presentation)	Sept 2016 (Completed)
Characterize PM from GCI of several gasoline-like fuels	Dec 2016 (Completed)
Develop GCI operating condition for high RON gasoline fuels (Not covered in this presentation)	Mar 2017 (Completed)
Endoscope imaging of GCI combustion luminosity and chemiluminescence for multiple injection to study soot and temperature, and CH*/OH*, respectively	June 2017 (In Progress)
Assess engine operating condition for optimal efficiency and low emission/soot for entire speed/load on E10	Sept 2017 (In Progress)

APPROACH FOR GCI TO TARGET HIGH LOAD OPERATING CONDITIONS: LESSONS LEARNED FROM PREVIOUS SOI SWEEP (SINGLE INJECTION WITH CONSTANT LAMBDA)

Early injection
- High HC/CO
- Low FSN
- Chemical control of autoignition & combustion phasing
- Combustion noise (premixed)

Parameter to control:
- EGR
- P_intk
- T_intk
- Split ratio



Late injection
- High NOx (reactive zone)
- High FSN if not enough mixing
- Noise (reactive zone)
- Linear relationship SOI vs. CA50

Parameters to control:
- SOI
- Injection pressure
- Nozzle design
- Swirl
- Split ratio

- Single injection is not ideal for wide load range: noise vs. FSN; emission trade-off
- Conceptual understanding for multiple injection strategy (i.e. triple injection):
  - 1st injection: -141 to -70 aTDC; limited in amount of fuel due to noise (early auto-ignition)
  - 2nd injection: -70 to – 30 aTDC; help transiting from premixed to heavy stratified combustion
  - 3rd injection: -30 aTDC or later; provide control for combustion phasing

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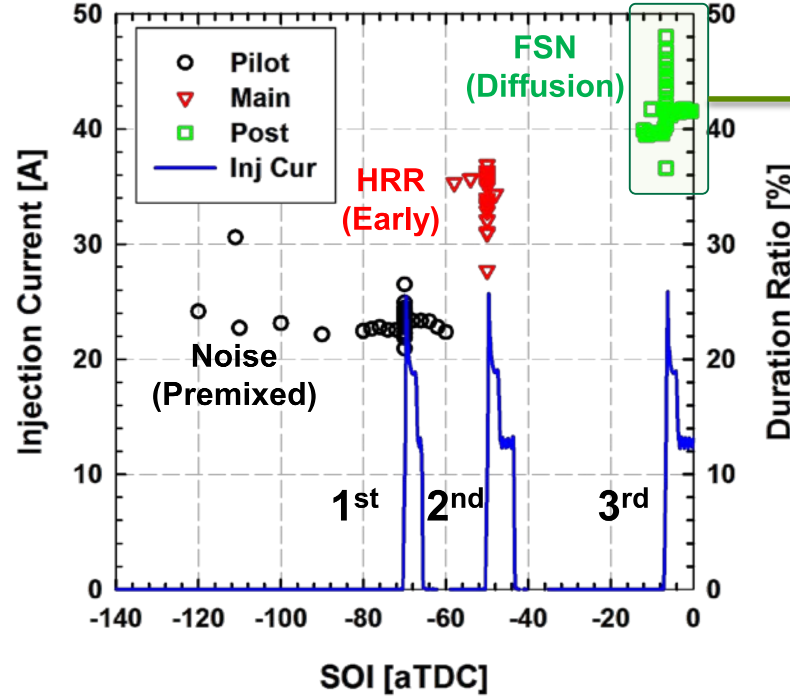
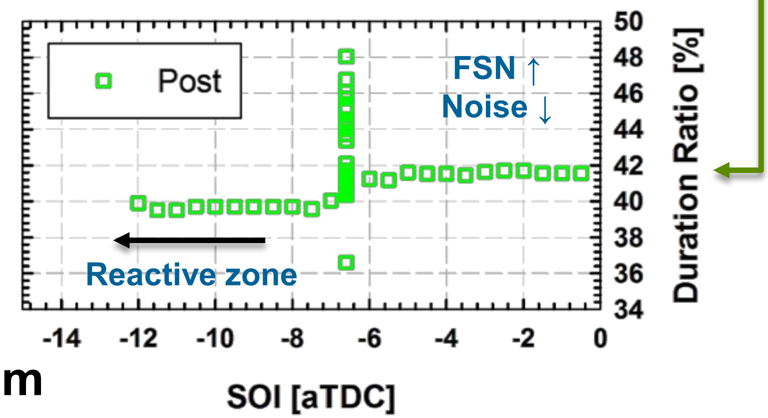
TECHNICAL ACCOMPLISHMENTS & PROGRESS

INVESTIGATION ON INJECTION STRATEGY FOR HIGH LOAD CONDITIONS

Parameter	Value
Engine 1.9L GM 4-cylinder (17.8:1 CR)	
Engine Speed [rpm]	1500-3000
Engine Load [bar BMEP]	5-14
Fuel	**E10**
Injection Pressure [bar]	600-800 (varied)
Start of Injection [°aTDC]	-70/-50/-6.6 (varied)
Fuel Split (~ % by duration)	25/35/40 (varied)
EGR [%]	0-30
Boost Pressure [bar(a)]	varied
Intake Air Temp [°C]	30
Global λ (= 1/Φ)	> 1.4



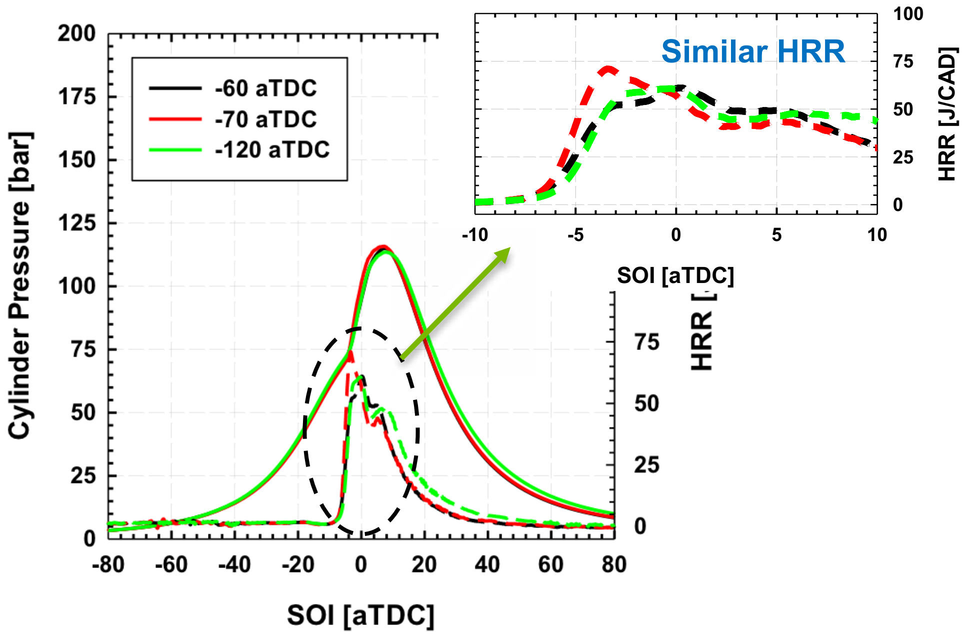


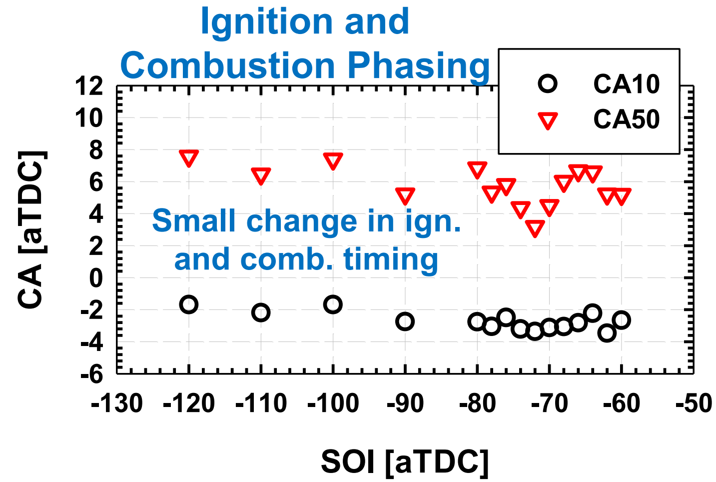
- **Injection strategy at 8 bar BMEP, 2000 rpm**
  - Split ratio
  - Start of injection
  - Injection pressure (& swirl)

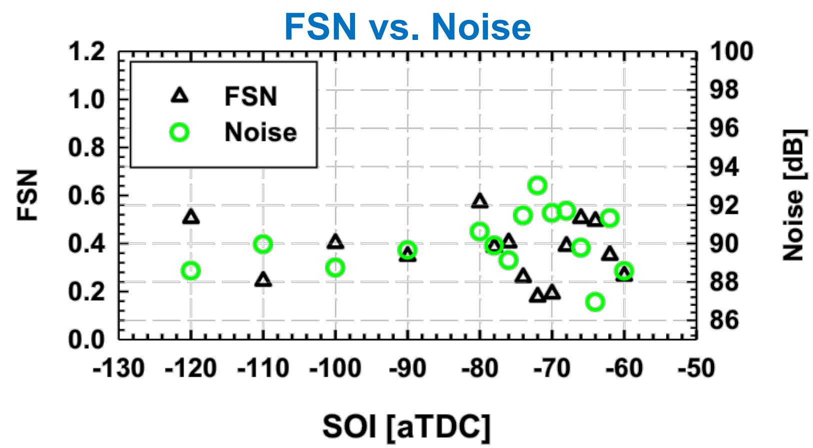
- **Load sweep at 2000 rpm**
- **Speed sweep at 8 bar BMEP**

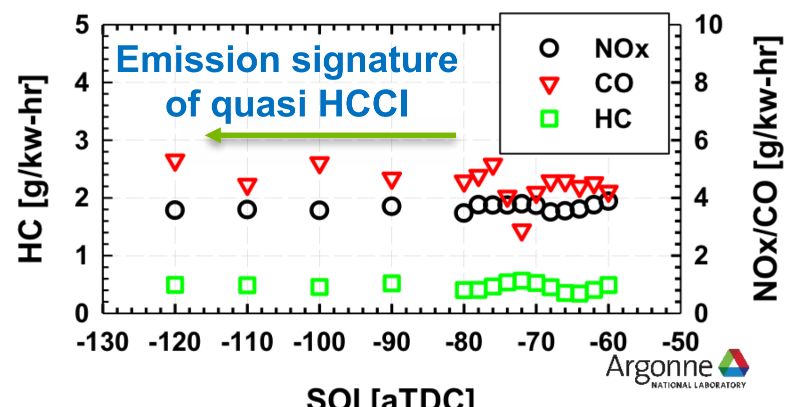
BMEP	8 bar
Speed	2000 rpm

1ST INJECTION: SOI EFFECT ON ENGINE PERFORMANCE





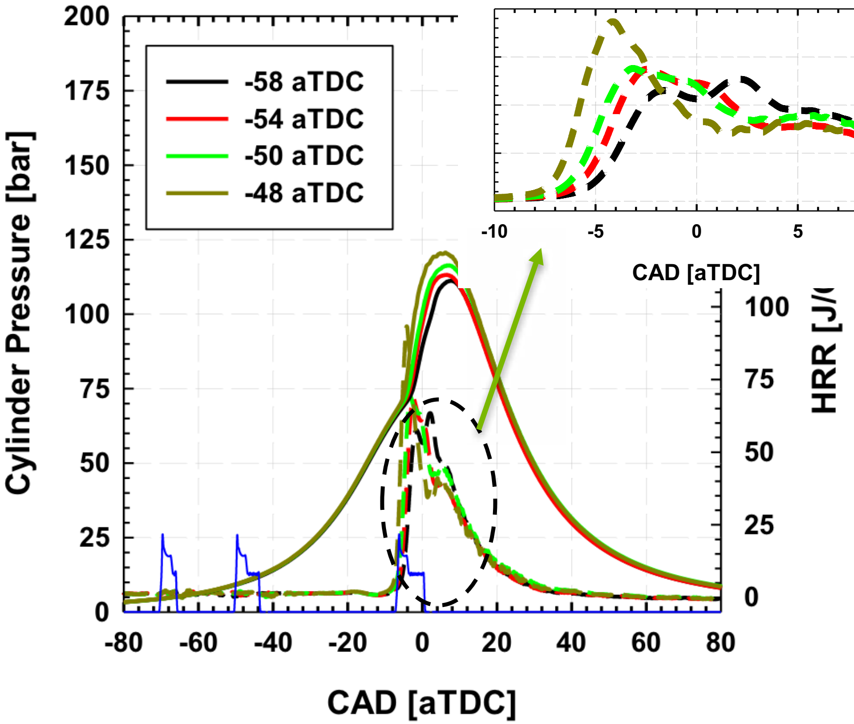




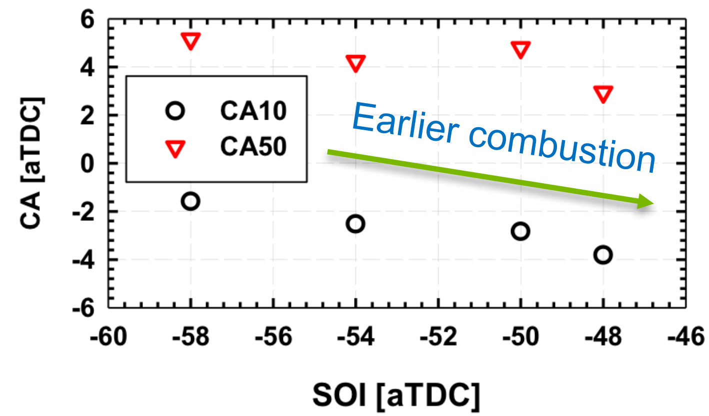
- SOI of 1st injection was changed over wide range (-120 to -60 aTDC) with minimum effect on CA10 or CA50
- Noise and FSN trends are not clear as SOI of pilot was changed
- Lowest FSN is found with SOI_{pilot} = -70 aTDC
- Emission of NOx/HC/CO shows insignificant change over SOI 1st injection sweep

BMEP/Speed	8 bar/2000 rpm
Tin/Pin(a)	30 °C/1.6 bar
Injection	Triple/600bar

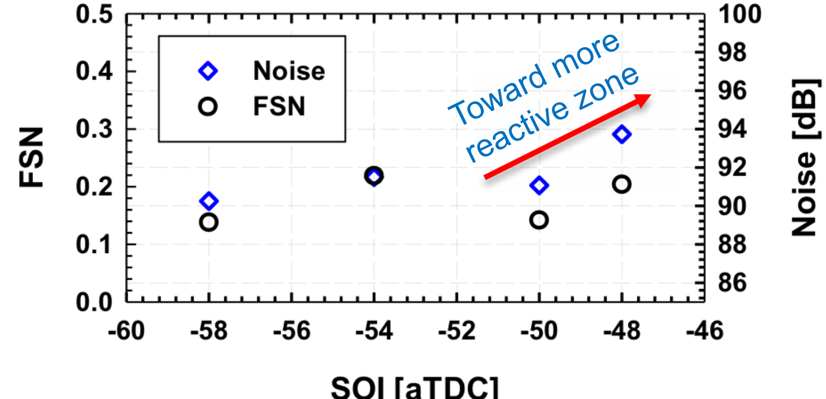
2^{ND} INJECTION: SOI EFFECT ON ENGINE PERFORMANCE



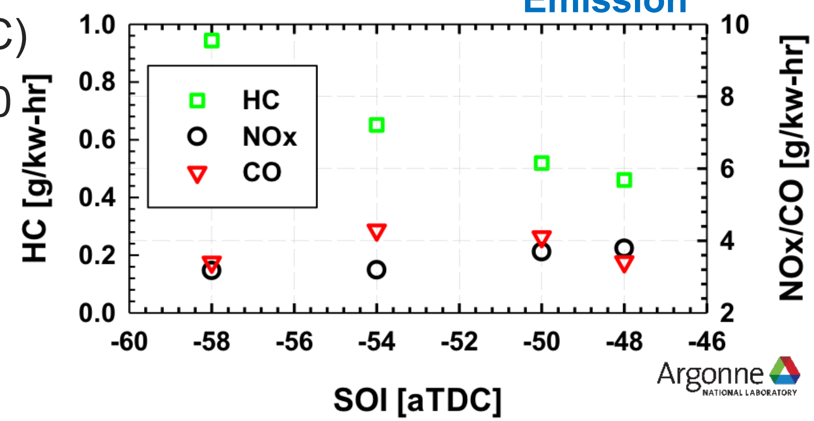
Ignition and Combustion Phasing



FSN vs. Noise



Emission



- Delaying main injection advanced ignition, and combustion phasing (toward “sweet spot” ~ -30 aTDC)
- Noise exceeds 95 dB with later injection (-48 aTDC)
- Avoid injection overlapped with pilot injection at -70 aTDC

BMEP/Speed	8 bar/2000 rpm
Tin/Pin(a)	30 °C/1.6 bar
Injection	Triple/600bar

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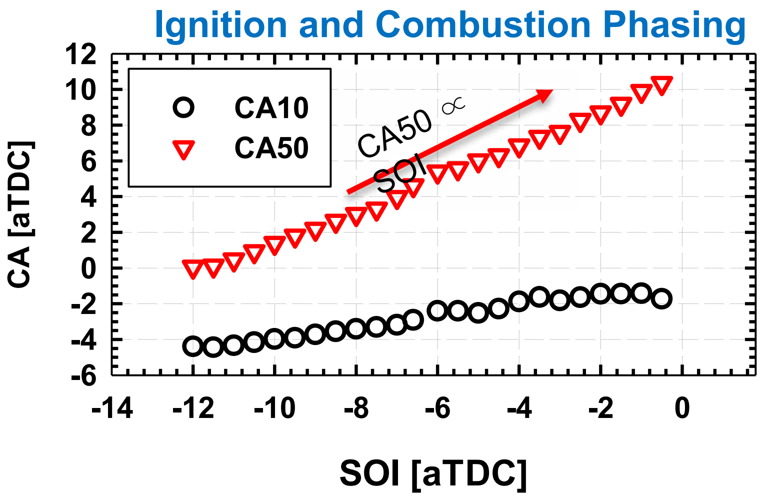
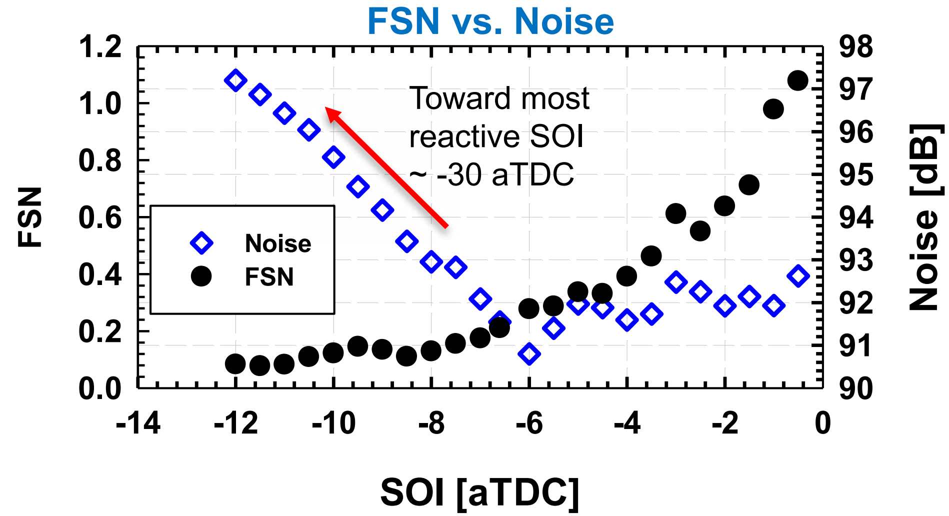
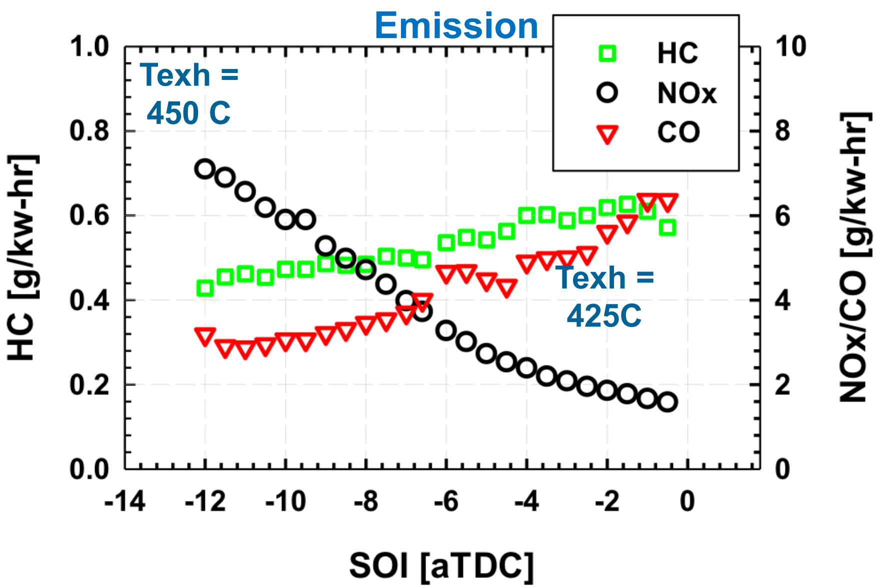
3RD INJECTION: SOI EFFECT ON ENGINE PERFORMANCE





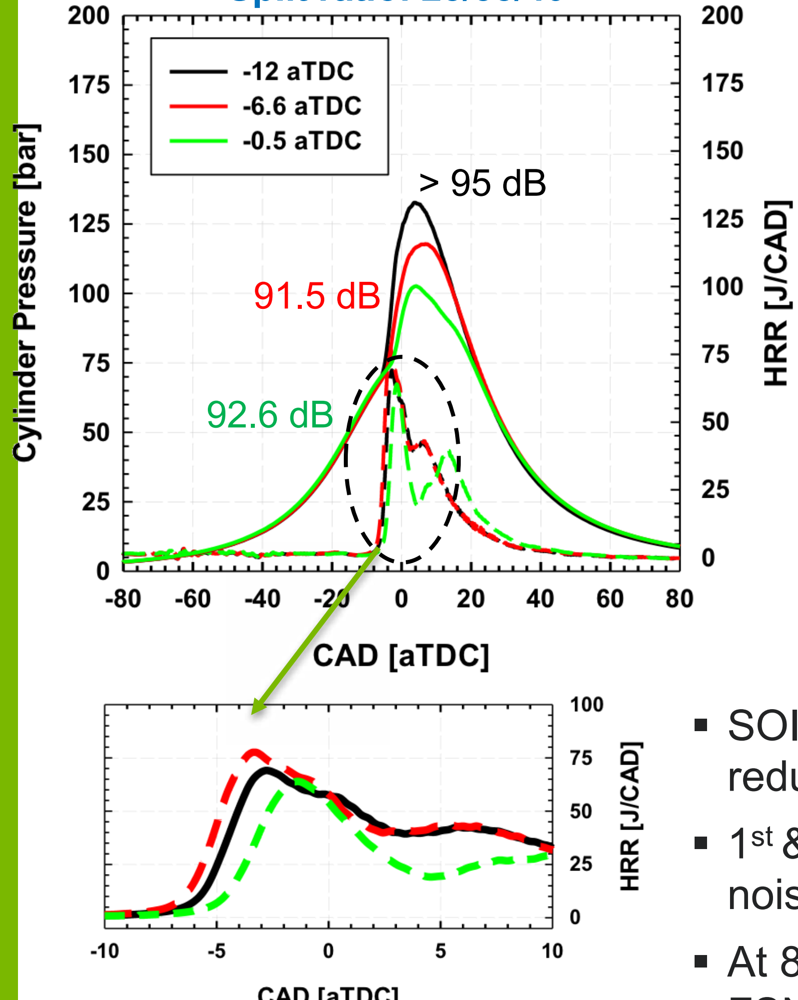


BMEP/Speed	8 bar/2000 rpm
Tin/Pin(a)	30 °C/1.6 bar
Injection	Triple/600bar

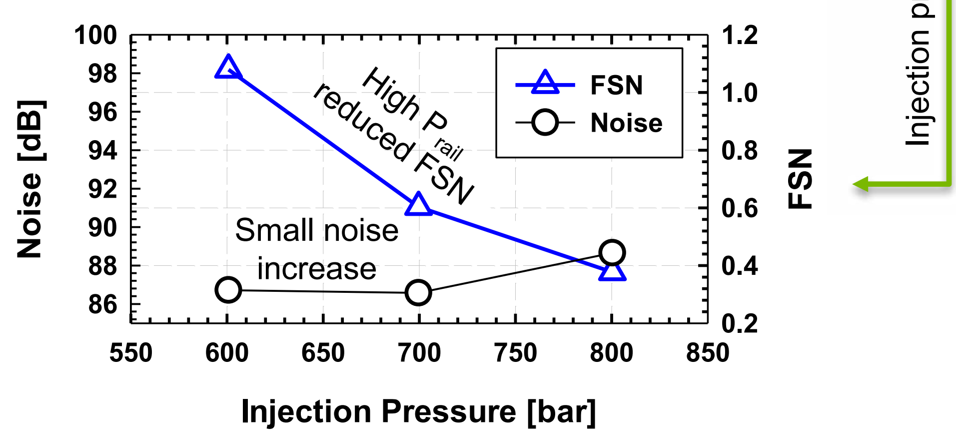
- Linear SOI post vs. CA50: **control** of combustion phasing
- **Noise** is lowest (91 dB) with SOI_{post} = -6.6 aTDC
- **FSN** below 0.1 with SOI = -12 to – 8 aTDC
- **Emission**:
  - Very low HC < 0.7 g/kw-hr, CO < 6.5 g/kw-hr
  - NOx is reduced with late injection (Texh ↓)
- **SOI_{post} = -6.6** is most desirable for lowest noise, relatively low soot/emission

EFFECT OF SPLIT RATIO, INJECTION PRESSURE EFFECT ON FSN AND NOISE

SOI of 1st/2nd: -70/-50 aTDC
Split ratio: 25/35/40



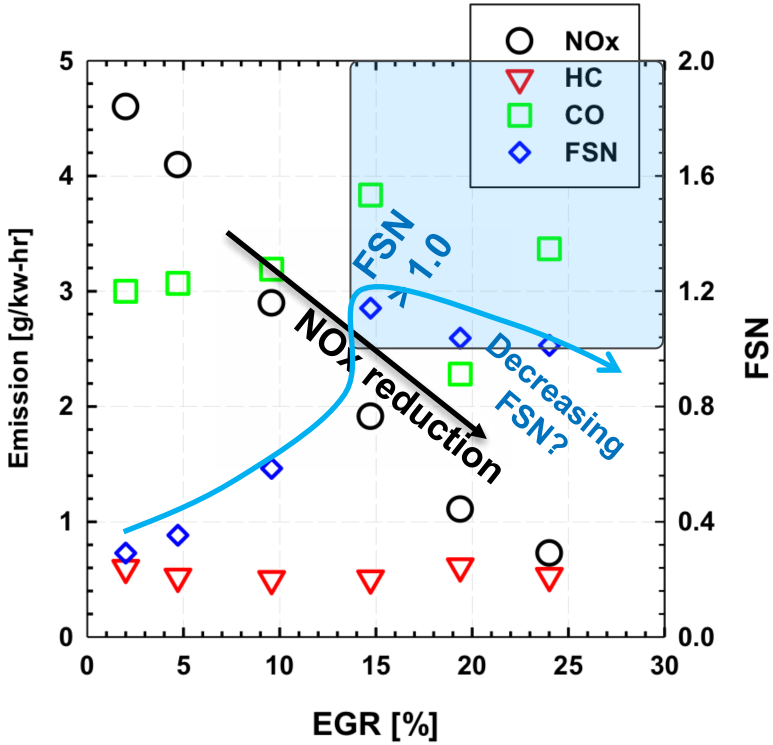
Split Ratio	Pilot [%]	Main [%]	Post [%]	Noise [dB]	FSN
More in last injection	22	32	46	86.7	1.079
	25	35	40	91.5	0.211
More in premixed	26.5	37	36.5	94.7	0.122

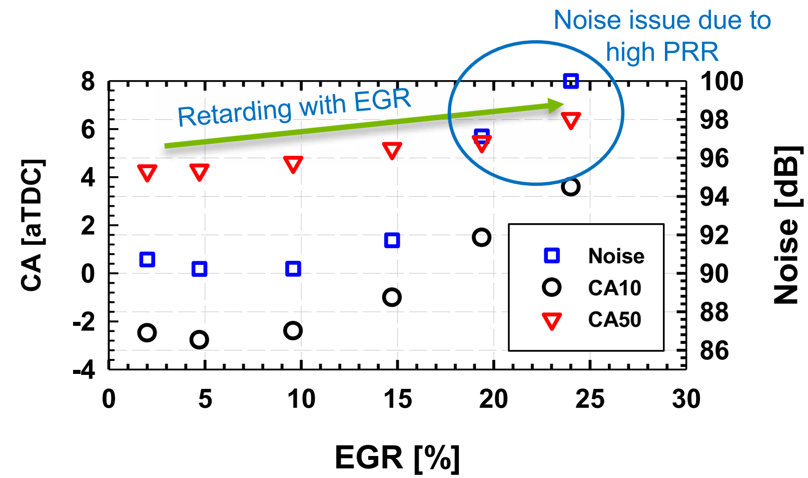


BMEP/Speed	8 bar/2000 rpm
Tin/Pin(a)	30 °C/1.6 bar
Injection	Triple/600bar

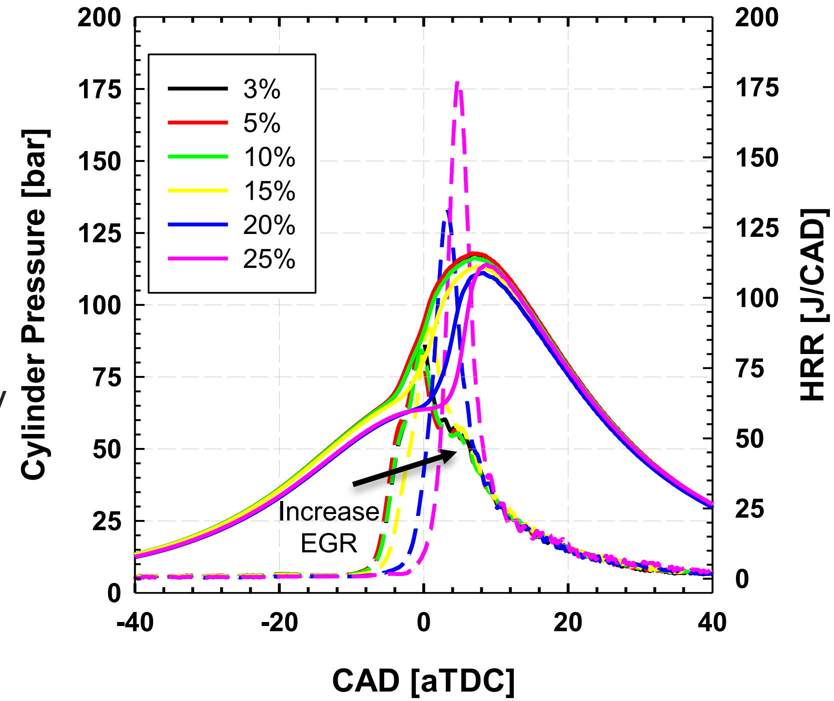
- SOI of the 3rd injection (later injected) can effectively reduce combustion noise but create high FSN (>1.0)
- 1st & 3rd injection ratio has trade-off between soot and noise
- At 8 bar BMEP, increase in P_{rail} from 600 to 800 improved FSN significantly with slight increase in noise
- High injection pressure should also help at higher load conditions → selected 800 bar as baseline

LP-EGR EFFECT ON PERFORMANCE: FSN VS. NO_X





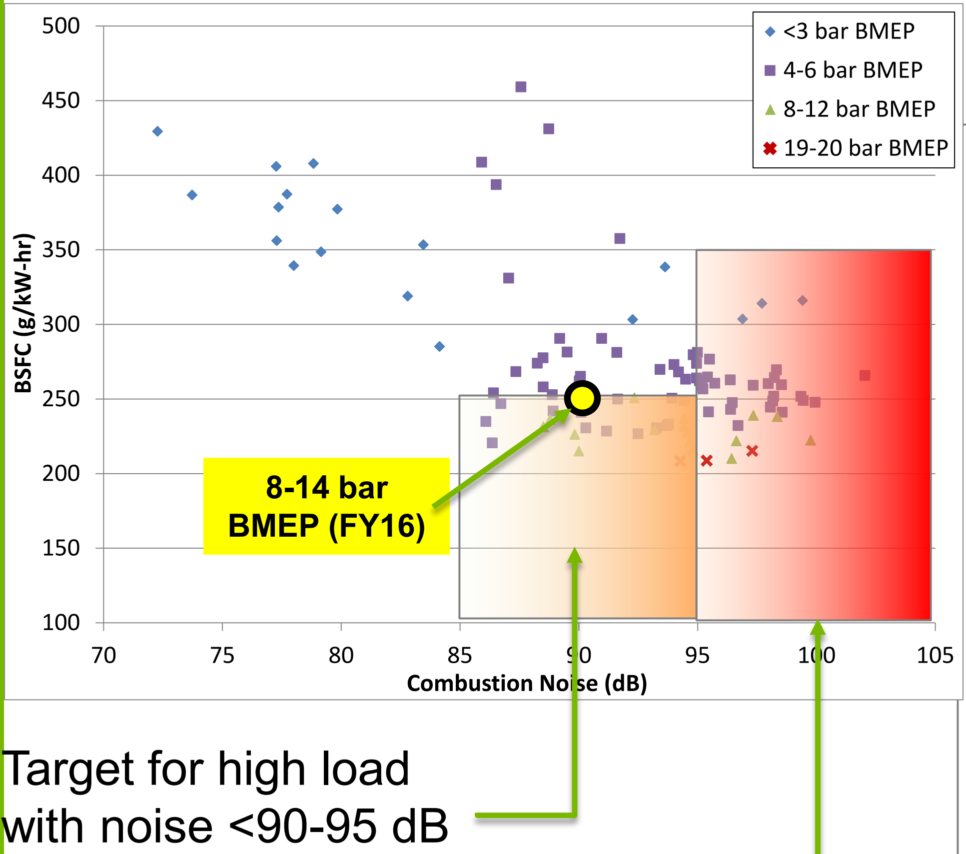
- Increase in EGR reduced NOx below 1 (g/kW-hr)
- FSN above 1.0 with EGR ~15%
- Noise increases > 92 dB with EGR > 15% (high MPRR)
- High EGR levels also limited intake pressure delivered by T/C
- Hence, high loads were investigated with little to no EGR



BMEP/Speed	**8 bar/2000 rpm**
Tin/Pin(a)	**30 °C/1.6 bar**
Injection	**Triple/800bar**

BRAKE SPECIFIC FUEL CONSUMPTION WHERE WE'VE BEEN AND WHERE WE'RE GOING

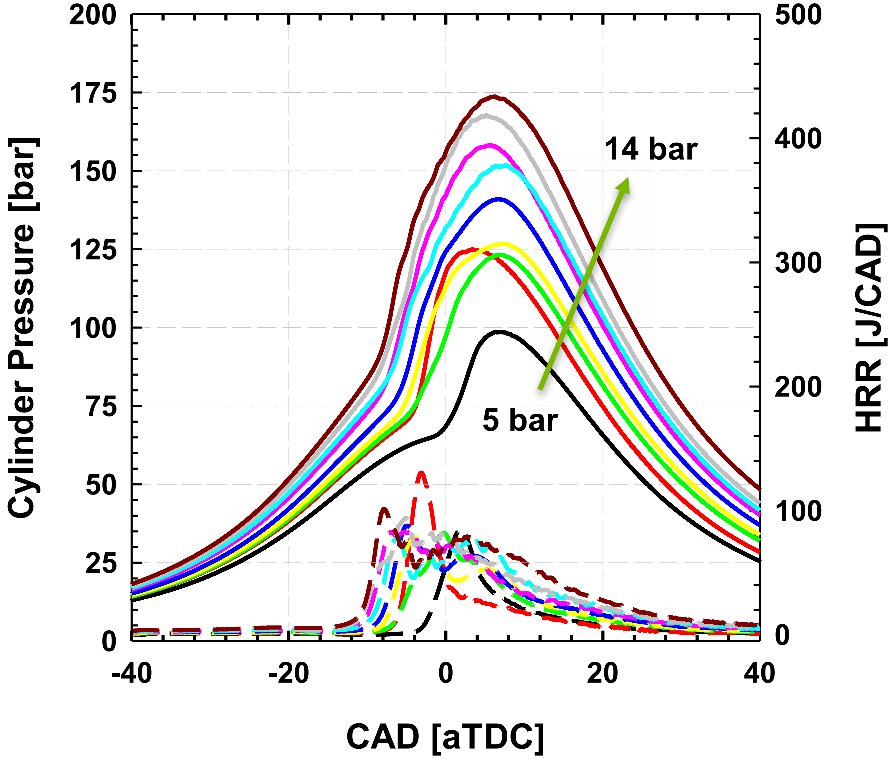
Past engine data have shown excellent brake specific fuel consumption performance – what has changed over time?

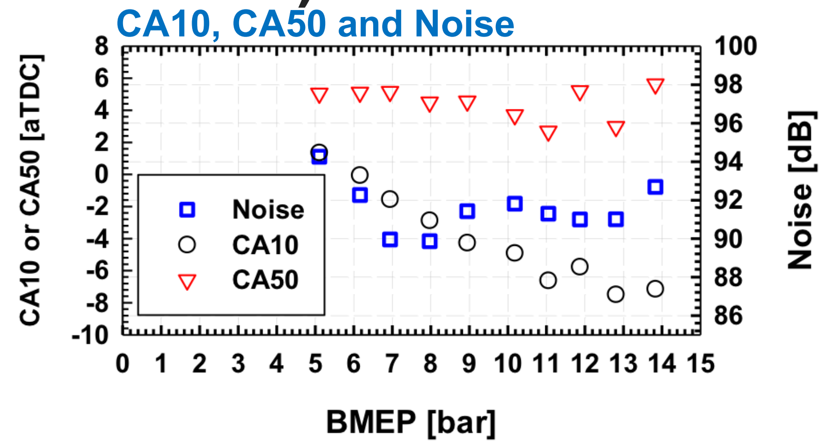


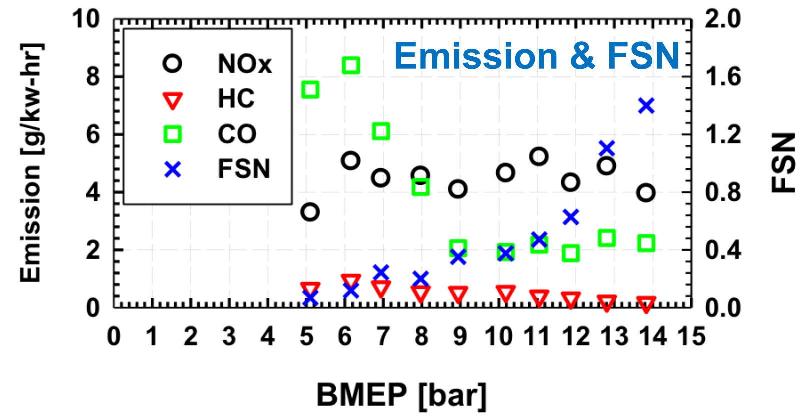
NEW CONSTRAINTS INFLUENCING FUEL CONSUMPTION

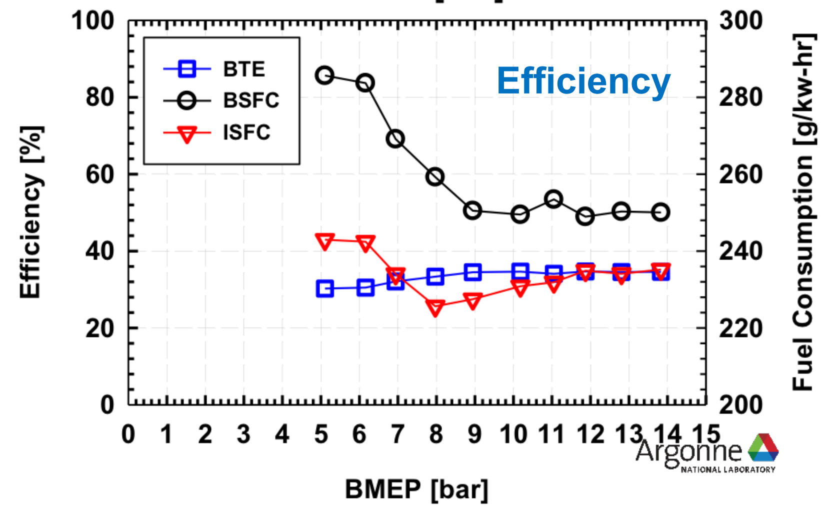
- 2013 AMR presentation (graph at left) shows higher efficiency at several engine points – most of them in high noise areas!
- Factors changing current efficiency levels include
  - USCAR provided combustion noise constraints (<90 dBA preferred)
  - Emissions targets
    - FSN <0.5
    - $(HC+NO_x) < 4.0$ (g/kW-hr)
    - CO <10.0 (g/kW-hr)
- Need to regain previous high efficiency but achieving these constraints
  - ***Need a better pathway!!***

ENGINE LOAD SWEEP (5-14 BAR BMEP) AT 2000 RPM





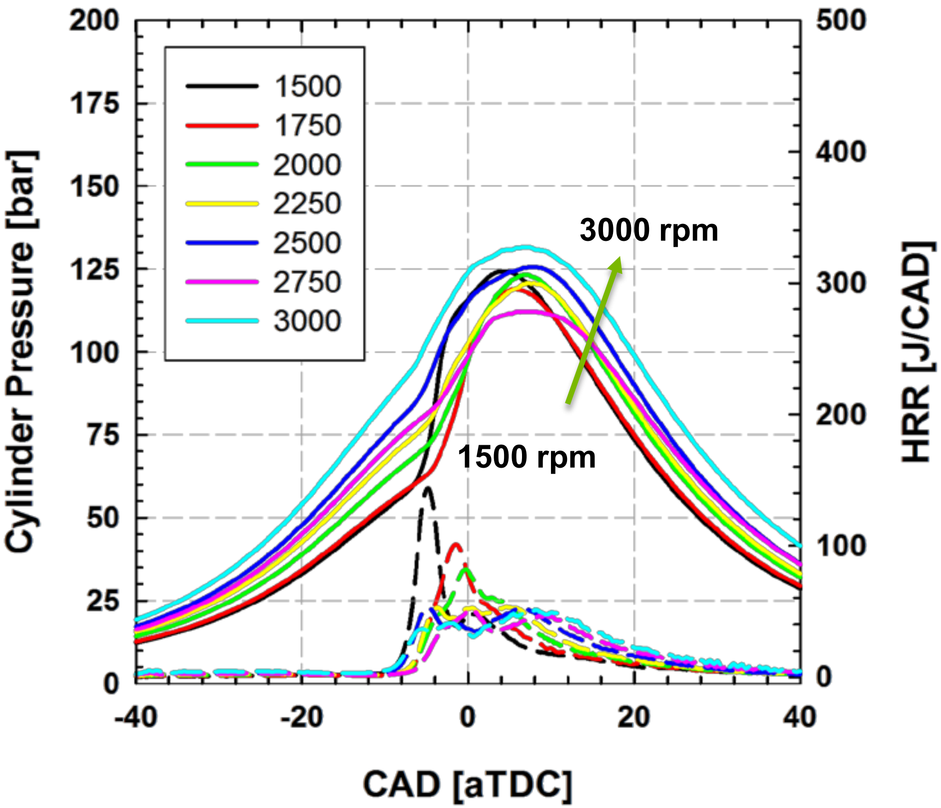


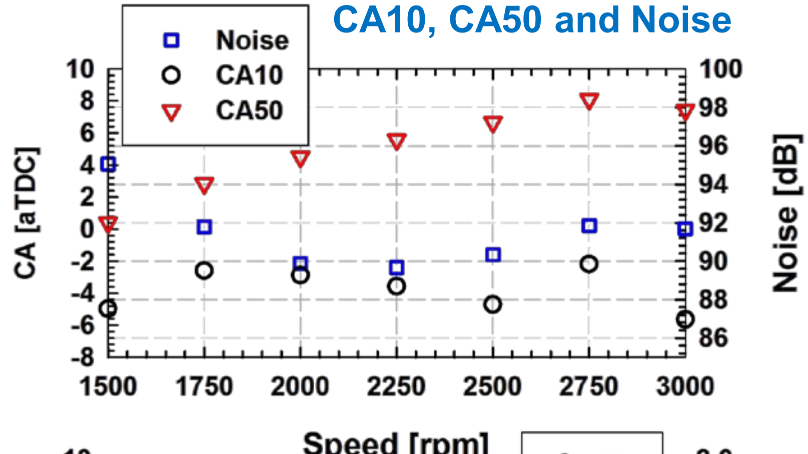


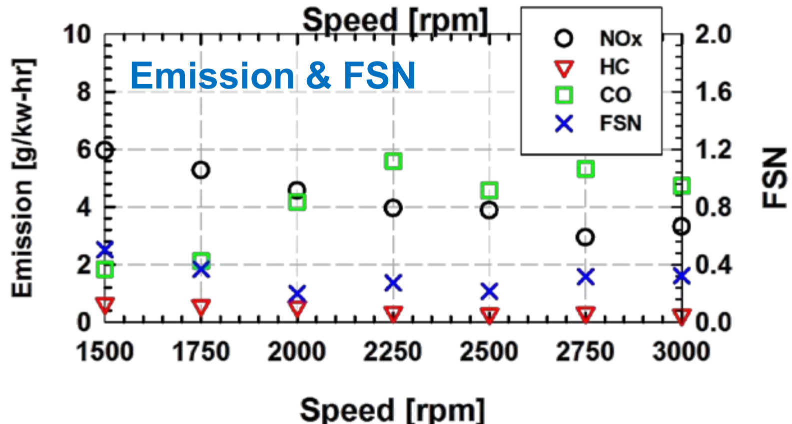
- No EGR
- Most loads (8-14 bar) has < 92 dB
- FSN increased to 1.4 at 14 bar BMEP
- Improved efficiency and fuel consumption at high load (> 10 bar BMEP)

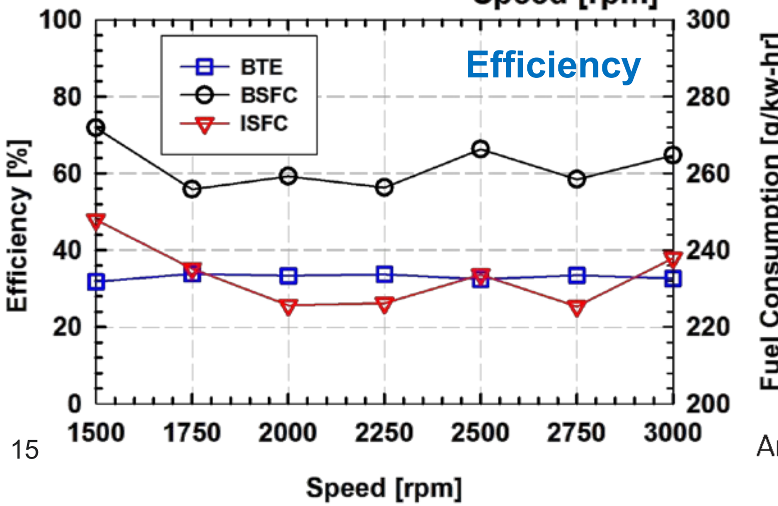
BMEP/Speed	var/2000 rpm
Tin/Pin(a)	30 °C/1.6 bar
Injection	Triple/800bar

ENGINE SPEED SWEEP (1500-3000 RPM) AT 8 BAR BMEP









- Higher engine speed:
  - Further retard CA50; earliest CA10 at 2500 rpm
  - Lower noise (lowest @ 2250 rpm)
  - NOx is also reduced
- FSN ~ 0.3 (average)
- No significant change in efficiency and fuel consumption over speed sweep

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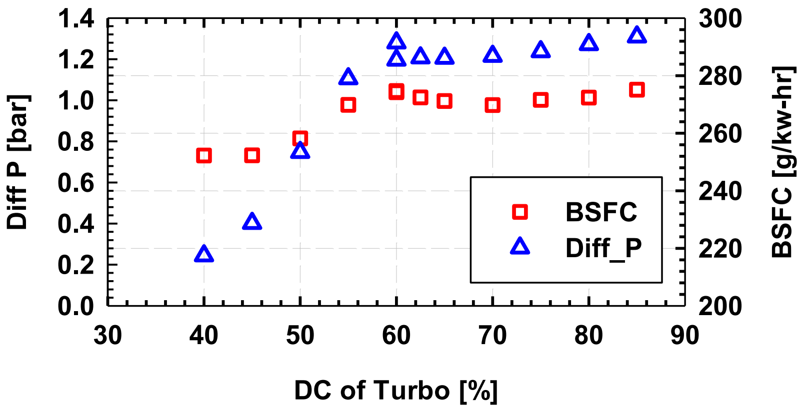
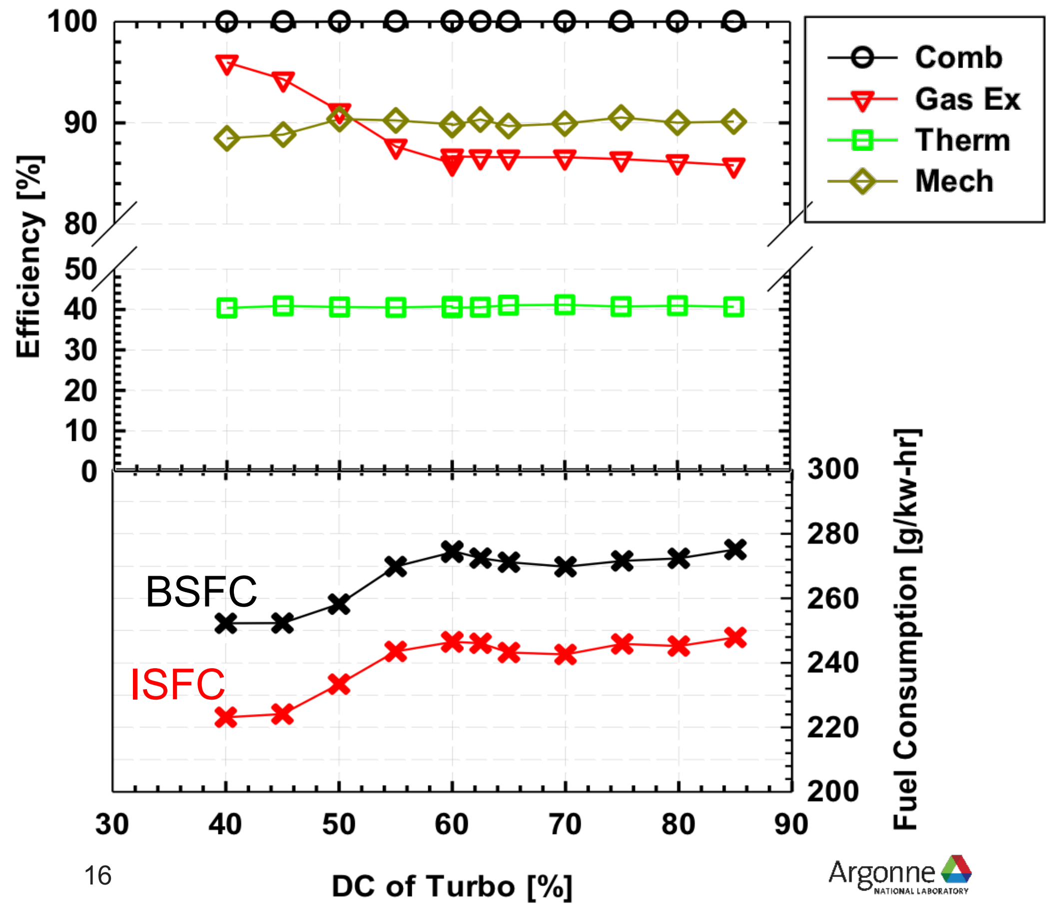
TURBOCHARGER PERFORMANCE ON GAS EXCHANGE EFFICIENCY

Turbo charger DC tuning for better gas exchange efficiency



- Duty cycle of VGT Turbochaarger was adjusted from smallest to highest
  - Boost output varied
  - Difference between pressure at inlet of T/C and intake manifold indicate how efficient the gas exchange process (the smaller, the better)
- Lowest fuel consumption with ~40-45% DC



- Gas exchange efficiency showed correlation with Duty Cycle (DC) setting
- Significant influence of DC upon ISFC
- Other efficiencies (combustion, thermodynamic, mechanical) are relatively unchanged

BMEP/Speed	8 bar/2000 rpm
Tin/Pin(a)	30 °C/var bar
Injection	Triple/800bar

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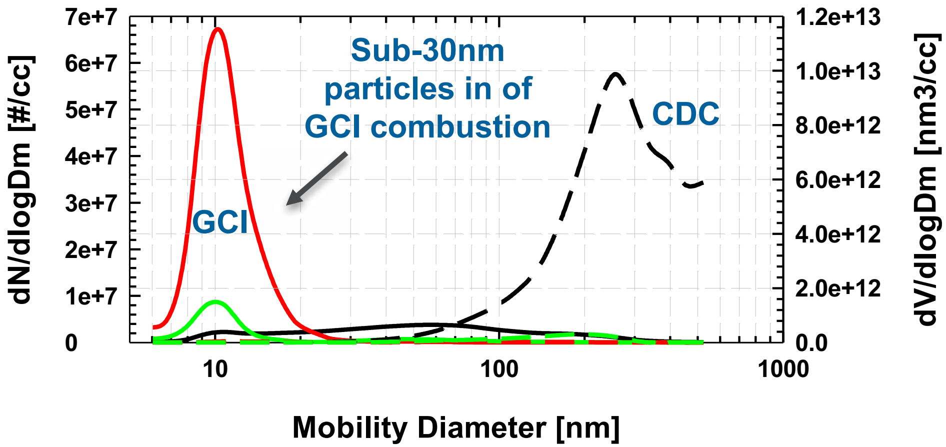
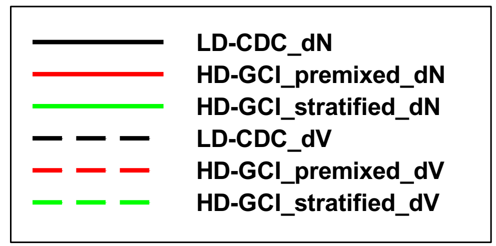
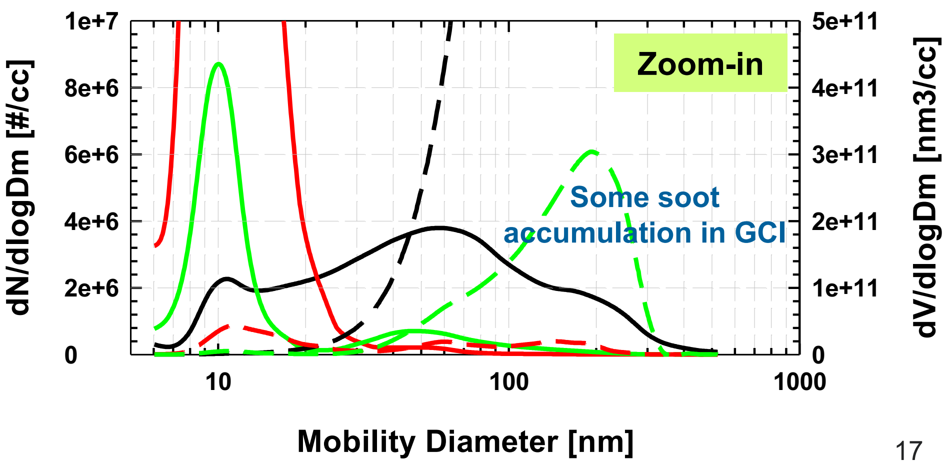
COLLABORATION - PM MEASUREMENT (HEE JE SEONG, SEUNGMOK CHOI, ANL): SMPS, EEPS, MSS, TEM IMAGES OF SOOT PARTICLE FROM GCI COMBUSTION

- PM from GCI combustion tend to be less populated and smaller in aggregate & primary sizes.
- Carbon fringe patterns of GCI soot are clearly observed like those of diesel and GDI soot.
- Statistical analyses of primary & aggregate sizes will be performed for a better understanding of the fuel impact.

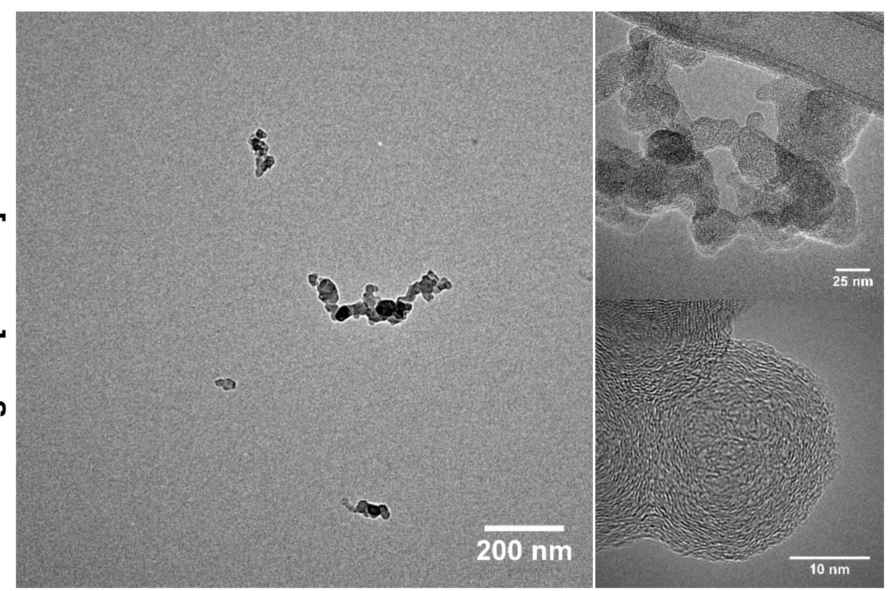






*Data from S. Choi, et al., SAE 2017

4.5 bar BMEP, FSN < 0.1



*TEM Images from Hee Je (ANL)

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RESPONSES TO FY16 REVIEWER COMMENTS

- **Reviewer Comment**
  - Methodology for injection approach
  - Speed/Load for efficiency analysis
  - Operating without S/C is more practical
  - Provide indicated and brake values for fuel consumption

- **Response**
  - Performed parametric study for SOIs, split ratio, injection pressure, EGR for desirable conditions (noise, FSN)
  - We investigated load and speed sweeps to analyze the conditions for highest efficiency within constraints
  - All testing was performed only with T/C to acquire more realistic efficiency values
  - BSFC and ISFC are shown for all testing points

COLLABORATIONS

- ❑ **GM**: Engine maps, piston crowns and other hardware, cylinder head modifications, technical support
- ❑ **ANL (HeeJe, Seungmok)**: Particulate measurement and characteristics for GCI combustion at different loads
- ❑ **Lund University**: PhD visiting student (Nov-Dec 2016); GCI engine experiment & research; optical diagnostics (in-progress)
- ❑ **Eaton:** Supercharger support, boosting guidance

➢ In addition, this project is involved in the AEC Working Group

- Cummins, CAT, DDC, Mack, John Deere, GE, International, Ford, GM, Chrysler, ExxonMobil, ConocoPhillips, Shell, Chevron, BP, ANL, SNL, LLNL, ORNL, NREL
- Co-Optima project is also related to this work

REMAINING BARRIERS AND CHALLENGES

- Improve air handling to make LP-EGR more effective
  - Tradeoff between amount of EGR and T/C efficiency
  - High EGR showed effective reduction of NOx but limited the capacity for boost (delivered by VGT T/C operation)
- Control low FSN at high load (>14 bar BMEP) while keeping noise low (<95 dB). Requires higher EGR and boost for more flexibility in engine control.
- Examine CR as influence for Combustion Noise/BSFC tradeoff
- Study influence of these parameters upon PM to insure future EPA compliance

PROJECT FUTURE WORK

- Continue with suggested guidelines for constraints on emissions, noise - ***maximize fuel efficiency!!***
- Investigate alternate boosting approaches and possibility for VVA
- Explore engine mapping load/speed and optimize efficiency at each point by injection approach and proper engine operation of T/C (focus on intermediate to high loads)
- Investigate low temperature heat release region where chemiluminescence may be seen (no soot luminosity)
  - Mixing controlled combustion of 3rd injection may be acceptable if constraints are met
  - Correlate with natural luminosity (endoscope) & PM measurement (collaboration work): initial measurements have been finished to identify desirable condition for taking images

Any proposed future work is subject to change based on funding levels.

SUMMARY

Understand the physical and chemistry characteristics of Gasoline Compression Ignition (GCI) in a multi-cylinder engine to aid industry in developing a practical high efficiency, low emission combustion system

1. Injection approach was developed to obtain desirable noise, soot, and emission: triple injection (moderate to heavy stratification level) with high injection pressure (800 bar).
2. Indicated/brake engine fuel consumption and engine efficiency were improved with T/C operation (BFSC was previously high with S/C). Mechanical efficiency was improved (>90%).
3. Results from speed/load sweep showed low combustion noise (~90dB most cases), however increase in FSN (>1.0) at high load (>14 bar BMEP). High combustion efficiency (>99%) was achieved for all points.
4. Higher EGR can help with NOx, but was limited due to difficulty in operating T/C for sufficient boost
5. Mediocre T/C performance indicated a potential pathway to improve air handling (gas exchange efficiency) and overall BSFC
6. TEM imaging and PM analysis of GCI combustion show similar structure of primary soot particle, but overall less populated soot and smaller size (<30nm) aggregates as compared to Diesel

THANK YOU FOR YOUR ATTENTION!

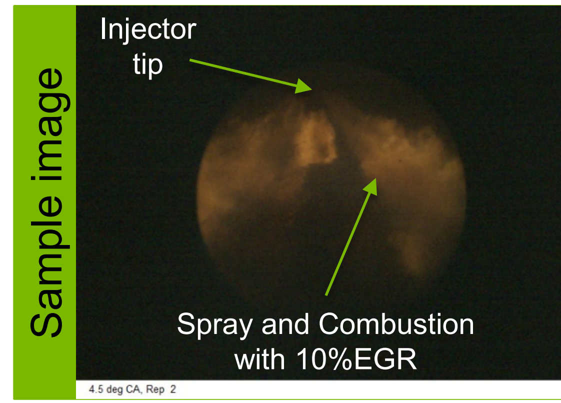
QUESTIONS?

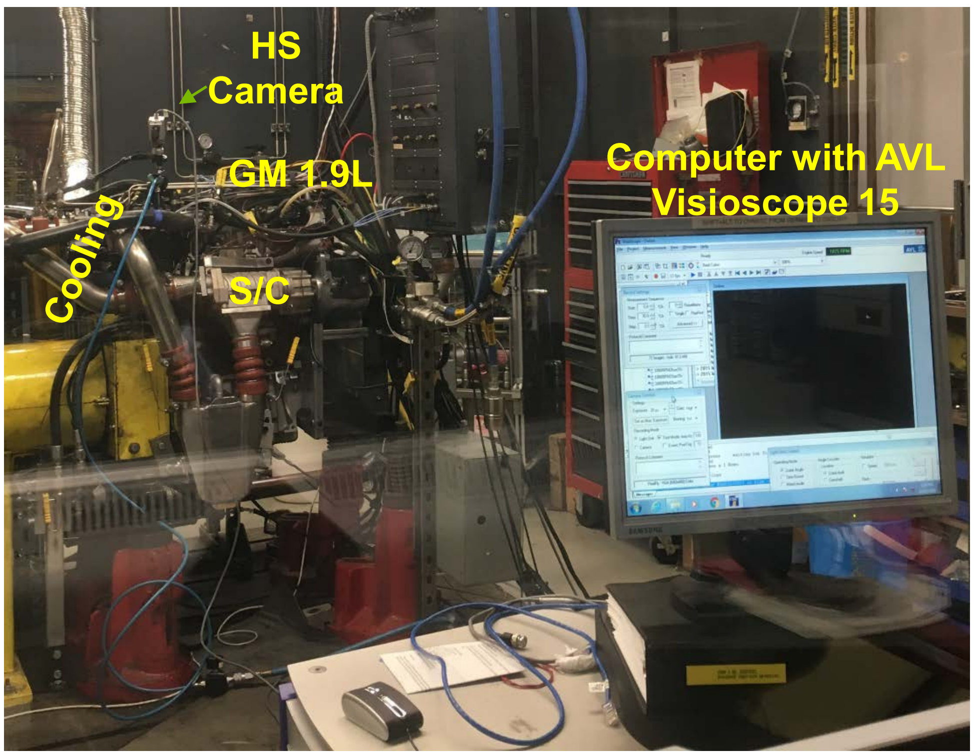
TECHNICAL BACK UP SLIDES

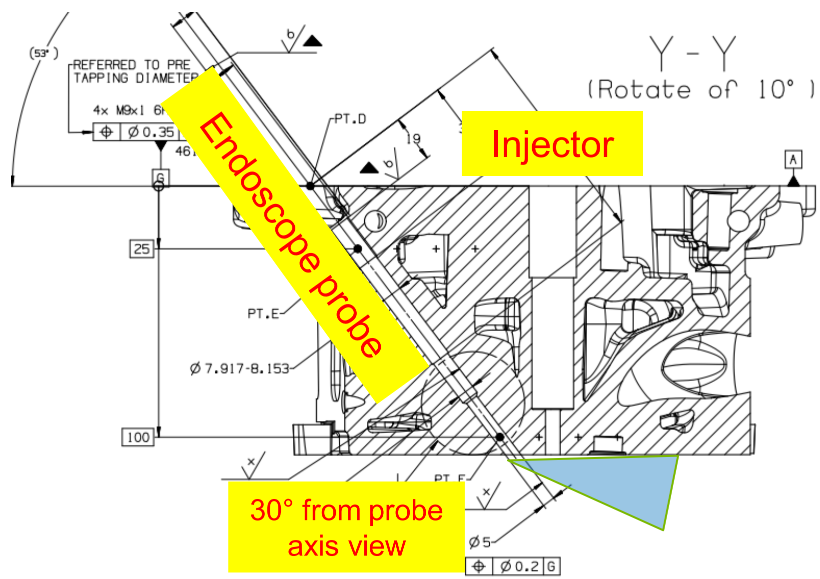
ENDOSCOPE IMAGING SETUP: COMBUSTION LUMINOSITY

Camera	PixelFly
Frame rate	10 Hz
Exposure	5-20 µs
Pixel size	680 x 480
Interval	-5° to 30° aTDC

- Endoscope access in cylinder #4
- Covering complete combustion event
- Spray (some scattering) is visible for 2nd injection



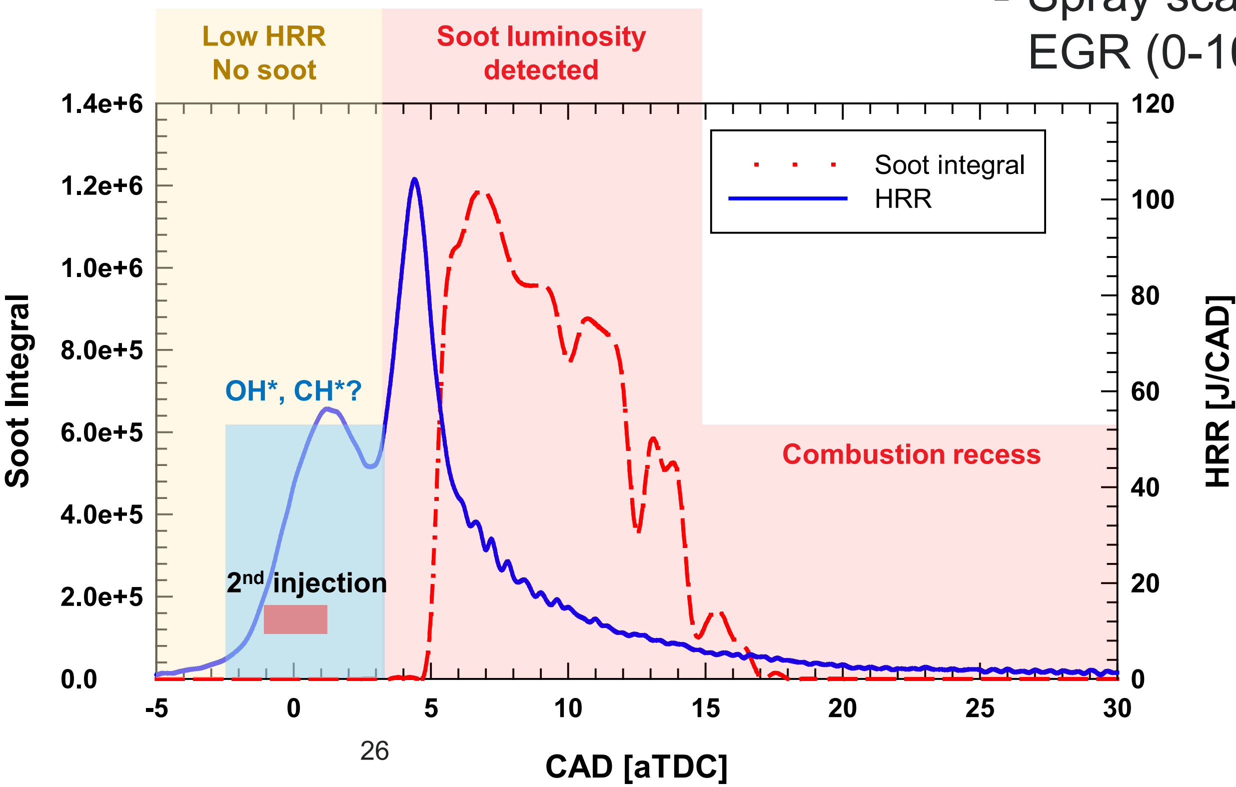




ENDOSCOPE IMAGE TO INVESTIGATE SPRAY AND COMBUSTION OF GCI: CORRELATION OF SOOT LUMINOSITY AND HRR

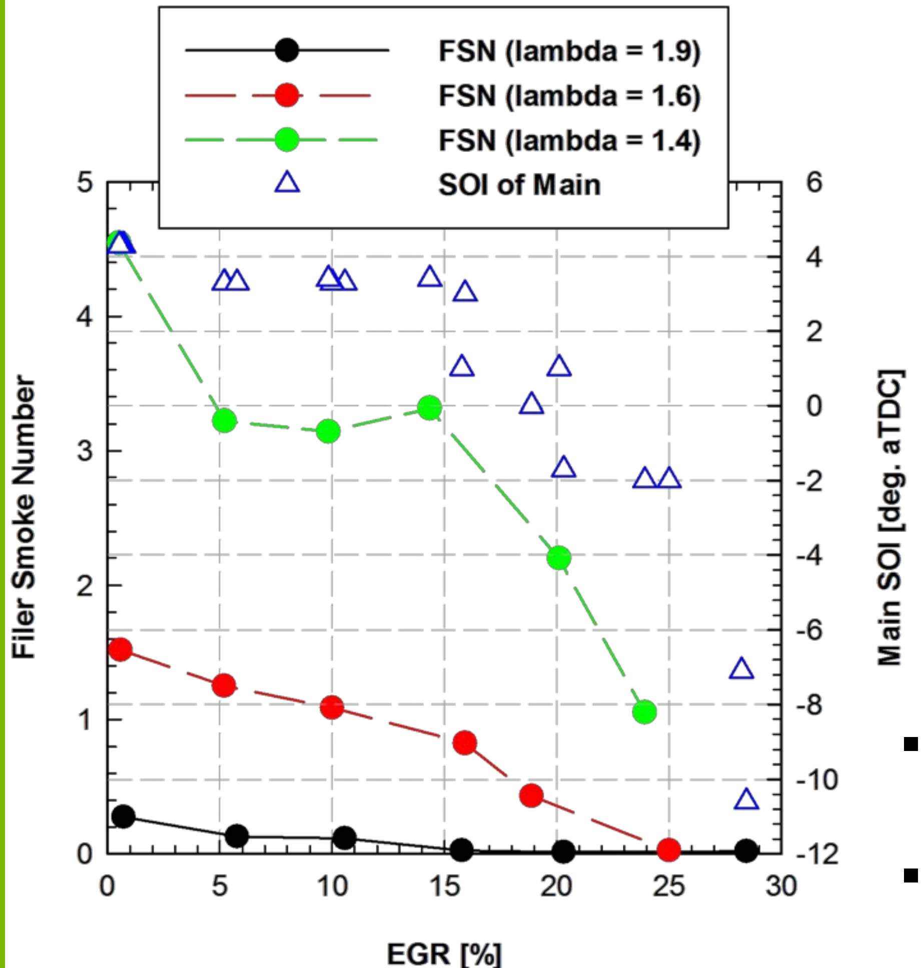
3°CA 5°CA 10°CA 13°CA 20°CA

- Soot luminosity is still visible even with FSN measured of 0.053
- Soot NOT appear at low HRR region
- Combustion ends long (~30 aTDC) after EOI
- Spray scattering were seen at lower EGR (0-10%) cases



Baseline condition	
EGR [%]	20
600 bar, Double injection -50 aTDC/~TDC with ~55:45 ratio	
Boost Pressure [bar(a)]	1.4
Intake Air Temp [°C]	55
Global λ (= 1/Φ)	1.8

EFFECT OF LAMBDA AND EGR ON FSN: COMBUSTION PHASING IS FIXED BY SOI OF MAIN INJECTION



Parameter	Value
Engine 1.9L GM 4-cylinder (17.8:1 CR)	
Engine Speed [rpm]	1000, 2000
Engine Load [bar BMEP]	Varied
Fuel – 98 RON	E10
Injection Pressure [bar]	600
Start of Injection [°aTDC]	-50/varied
Fuel Split (~ % by duration)	55/45
EGR [%]	0 - 30
Boost Pressure [bar(a)]	1.2
Intake Air Temp [°C]	50
Global λ (= 1/Φ)	1.2-2.0

- Advance of main injection at increasing EGR levels
- At low EGR (<15%), no significant difference in SOI of main (also for all lambda cases)
- FSN is reduced significant with 25% EGR or higher

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